

Dynamic Management of Systems Undergoing Evolutionary Acquisition

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Abstract

Procurement of modern military systems is made timely and effective by invoking evolutionary acquisition and spiral development. This process is dynamic: a system version (Block 1) is designed, manufactured, tested, and fielded while next generation's (Block 2) altered improved subsystems are simultaneously developed (along an upward spiral of effectiveness and suitability). Sequential tests determine when Block 2 provides a measurable and operationally significant improvement over, or complement to Block 1. Inferred cost and capability of Block 2 dictates its introduction time, and so on to Block 3, etc. Enemy adaptation to the capabilities of current blocks accelerates the transitions to new versions, and CONOPS. Concepts of effectiveness and suitability growth, and mutation, must be encouraged and quantified, initially using exploratory models, but later tested against challenging but realistic opposition and environments. The technical tools provided (e.g. success-run stopping rules, robust Bayesian methods, etc.) are credible for supplying "growth" (e.g. Test-Fix-Test) tracking and decision making for both effectiveness and suitability. Sustainability and logistics costs are given full attention.

1. Setting

The new acquisition regulations state "the primary mission of Defense acquisition is to acquire quality products that satisfy user needs with measurable improvements to mission capability and operational support, in a timely manner and at a fair and reasonable price;" DoD Directive 5000.1. "Evolutionary acquisition is the preferred DoD strategy for rapid acquisition of mature technology for the user. An evolutionary approach delivers capability in increments, recognizing up front, the need for future capability improvements;" DoD Instruction 5000.2. Thus a military system is fielded in a series of Blocks; each Block desirably being more capable and suitable than the previous ones. The improvement should be testable, and adequately tested.

2. Basis for decision to field a new block

2.1 Preamble: Broad Issues

There can be many reasons to initiate design of a new Block, $b+1$, say, given Block b is in some stage of testing or field employment. Any time such a block initiation starts, it typically encounters engineering/technical problems that will take time to resolve, and also incur unpredictable costs; these two features are inter-related, and are generally categorized as *project* (Block $b+1$) *risk*. At present such risk is put into broad categories by "expert judgment", so choices are made subjectively, and it is assumed that mistakes can be corrected subsequently, either by within-Block (b) modification, or when a new block is fielded.

Timing the start of a new block (the $(b+1)$ st) is an important decision problem: a relatively long time between blocks may, and is desired to mean, that upon introduction, the new $((b+1)$ st) Block is

considerably more capable than is Block b , where capability is a composite of Effectiveness and Suitability. However, there is a tendency for the new $((b+1)\text{st})$ Block to have undesirable features such as too much weight and to cost more than Block b unless vigilance is strongly executed; unfortunately such undesirable features often have shown up late in the acquisition cycle (during Operational Test (OT) or field experience). This may negate the promise of the new Block, at least for certain missions and CONOPS. Also, if Block b is in place too long, opponent adaptation to its capability may greatly degrade that capability. This argues for built-in dynamic flexibility and operational effectiveness tracking; field modification can sometimes be used beneficially. Generally design modifications are most cost-effective if made early in an acquisition evolution.

A relatively short time between issuance of successive blocks may provide for quick response to surprises, either from opponent action or from unanticipated misbehavior of the system itself. Actual large losses (attrition) of the systems in Block b may be tolerable if Block $b+1$ is nearly ready, or its development can be accelerated. On the other hand, a short between-Block interval can mean that more modest increases in capability are likely, and that there must be more frequent developmental testing (DT) and OT tests to validate the quicker succession of new Blocks. A compromise must be sought and justified.

2.2 Testing

A system is undergoing evolutionary development; it will be fielded in various blocks. Each Block will undergo developmental testing (DT), operational testing (OT), and fielding. In this discussion we will combine both developmental and operational testing into one test phase. Similar results can be obtained for the more general situation. Suppose Block b is starting development. We assume there are $D(b)$ design defects (DDs) that can be discovered and removed from Block b design, and copies during testing. In addition there are also design defects that are not removed during the acquisition of Block b , $D_p(b)$; we call these p -DDs, permanent DDs for Block b . These p -DDs are candidates for removal in future blocks. Those DDs, and p -DDs not removed by testing can activate in the field, leading to costly repairs and decreased system availability for missions.

Assume there are a random number of DDs. The mean number of DDs is r . Assume the time until a particular DD is discovered is random having mean $1/m$ independently of the others. Assume it is possible to determine the type of a discovered DD; that is, if a DD activates, then the DD can be removed; if a p -DD activates, it is not removed. Thus a found DD is fixed very soon, see Crow (2004).

Testing consists of a random number of test-lets each of length t where $t = km$, m being a mission time, and k an integer, e.g. 3, 5, etc. Assume all test-lets last t time units and all removable DDs that activate during a test-let are removed; removal means that no more failures can occur from that source; the aim is to have a high probability of zero DDs showing themselves after the system is fielded. This suggests that it would be unwise to terminate testing before the occurrence of a run/sequence of tests in which no defects are discovered. Here is a practical and appealing

Stopping Rule: field item at the termination of the first test-let ($t = km$ duration) during which no removable DDs activate.

In general the design of the test (choice of N =number of design copies used in the test-lets, and duration of test-let (value of k) must be guided by simulation. Analytical results are derived for Poisson numbers of DDs and exponential times for DD activation. Results are reported in a technical appendix.

After developmental testing, the system is then fielded. Once the system is fielded, failures due to remaining DDs are repaired; repair means that the system can continue to fail due to the DD.

3 Modeling an Evolutionary Step

Let Block b begin its sequence of tests, followed by fielding at calendar time 0. Introduce the decision-time-to-start-Block $b+1$, $T(b+1)$. $T(b+1) \geq 0$ is arbitrary, but may start even at $T(b)$; otherwise it may be planned to start at the termination of the testing of Block b , or perhaps later, at the time Block b is fielded, or at a random time determined by opponent action, *etc.* Let t_b denote the elapsed time since Block b was initially fielded and began executing missions.

Let $p_b(t_b)$ be the probability of mission success for block b at time t_b ; it is equal to $\bar{p}_b \mathbf{x}_p(b)$ where \bar{p}_b is the lethality/capability of the system and $\mathbf{x}_p(b)$ is the probability of being available or of being suitable. Block b fails at rate $N_f(b) \mathbf{n}_f(b) [D(f;b) \mathbf{m}(b) + D_p(b) \mathbf{m}_p(b)]$ where $N_f(b)$ is the number of block b systems initially fielded, $\mathbf{n}_f(b)$ is the anticipated rate of usage (e.g. hours/day or missions per day) in the field; $D(f;b)$ is the number of DD s remaining when Block b is fielded and $\mathbf{m}(b)$ (respectively $\mathbf{m}_p(b)$) is the failure rate of a DD (respectively p- DD) in Block b in the field. Let the estimated expected cost per system failure be $c_F(b)$; the latter should realistically be a random variable, as should be the down time associated with a failure. We omit such details for the present; (they occupy a place on a thorough research agenda).

The success-run-terminated-Test-Fix (Defect Removed)-Test...Field, Repair, ($TF(DR)TFR$) procedure allows a program manager and acquisition authorities to anticipate the consequences of varying $T(b+1)$, the time to begin a new evolutionary cycle. This must realistically initially be done on a “*What-If*” basis since no combined DT/OT data on block $b+1$ will yet be available. Consequently,

(1) Compute or simulate a ($TF(DR)TFR$) sequential procedure starting at $t_b = T(b+1)$; t_b represents the time that Block b has been fielded and utilized:

(a) Specify the mean number of DD s ($b+1$), $\mathbf{r}(b+1)$, to be $f_D(b+1) \mathbf{r}(b)$, where $f_D = 0.5$, say, and that DD Block $b+1$ activation rates are $\mathbf{m}(b+1) = f_A(b+1) \mathbf{m}(b)$ where $f_A(b+1) = 0.75$; various trial values are suggested, and can be revised as tests occur. The result will be estimates of the distribution (generating function) of DD s($b+1$) remaining after test completion time T_{b+1} . It makes practical sense to include a test that uses $\mathbf{r}(b)$ and $\mathbf{m}(b)$, as this will tend to be conservative if Block $b+1$ is an improvement.

(2) Using the results of (1) calculate the estimated probability that a (sub) system of Block $b+1$ (or system of subsystems) will operate successfully on a mission in the field. Continue development and testing of Block $b+1$ if the estimated probability is less than that of Block b .

(a) A maintenance/CONOPS model can use the results of (2) above to estimate the operational availability of any number of fielded systems. This will depend on maintenance support, system maintainability, and mission demand. This aspect is deferred, though see results of Stoneman (1998) for a beginning. Considerations of sustainability and attrited system replacement require cost considerations against a fixed Block $b+1$ budget are pursuable by modeling in advance of T_{b+1} .

(3) *Effectiveness* of Block $b+1$ can be measured or quantified variously, as it applies to particular systems and missions. One general measure is mature/ultimate *probability of mission success*. This probability may well increase if introduction is delayed; denote by $\bar{p}_{b+1}(u_b)$ that ultimate probability, where u_b is

the development time for Block $b+1$. This probability will require initial judgmental estimate. It may be tentatively represented by a logistic growth curve:

$$\bar{p}_{b+1}(t_b) = \bar{p}_{b+1} \left\{ \exp(g(b+1)u_b) / [1 + \exp(g(b+1)u_b)] \right\}$$

where $g(b+1)$ represents an effectiveness growth rate (function) for the technology of Block $b+1$, and u_b the time allocated to that growth; $g(b+1)$ can depend on developmental resources expended and may be estimated from historical data; \bar{p}_{b+1} is the ultimate probability of mission success, given $u_b = \infty$, an indefinite time. Note that extending u_b improves Block $b+1$'s capability, but gives the opponent Red, a longer opportunity to adapt to the capability of Blue's Block b , so a roughly optimal interval (or evolution rate) should be sought—and revised, as experience develops. Field evidence of Red adaptation can be used to modify $T(b+1)$.

4. Conclusion and Future Program

It is proposed to elaborate the above conditions and issues, and to provide operational tools to guide the timing of evolutionary cycles. The properties of the Poisson-Exponential TF(FR)TF stopping rule procedure have been made explicit and can be used to help define the best evolutionary cycle times. Simulation and more analysis will be designed to assess the procedure's robustness. Application to Interim Armored Vehicle, IAV (STRYKER) acquisition and testing is underway.

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